Table 1

Estimated Costs of Relocating BAS Channels (Fixed and Mobile)

Licensed Frequencies	Affected Channel(s)	Number of Affected Stations		Relocation Alternatives Total Cost in Dollars		
		Fixed	Mobile	A [34]	B	C
1990-2008 MHz	1	860	551	$72,310,000	$110,230,000	$126,310,000
1990-2025 MHz	1 & 2	1076	687	90,260,000	137,460,000	158,290,000
1990-2110 MHz	1 to 7	2209	1134	N/A	244,630,000	284,280,000

Note: Alternative "A" is shifting the BAS channel(s) into the 2110-2145 MHz band; Alternative "B" is moving the BAS channel(s) to the 6875-7125 MHz band; and Alternative "C" is moving the BAS channel(s) to the 12700-13250 MHz band.

As the above table reflects, there is a slight increase in BAS relocation costs associated with moving the first versus the first and second BAS channels. These costs also increase somewhat as the BAS channels are moved further up in frequencies. In addition to the BAS relocation costs, there are significant costs associated with clearing out fixed microwave stations from the 2110-2145 MHz band as is necessary for Alternative "A".

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[34] These relocation costs do not take into account the cost of moving incumbent fixed microwave stations to higher bands in order to accommodate the relocation of the first two BAS channels to the top end of the BAS band. Such microwave relocation costs could be substantial -- i.e., on the order of $250,000 per station.

C. MSS Licensees Should Not Bear the Entire Burden of Moving Incumbent Users From the 2 GHz Bands

In considering which alternative to adopt for the movement of BAS stations out of the MSS uplink band, the Commission should apply its emerging technology relocation policies in a fair and equitable manner. In particular, if non-MSS licensees would benefit from the relocation of BAS channels or paired microwave stations, then they too should bear their fair share of the costs of relocating incumbents users. In this way, the MSS industry will not have to bear all of the burden of moving existing users of the spectrum and should be more willing to support relocation plans which make both economic sense and which are sound from a spectrum management standpoint.

Motorola also generally agrees with the application of the clearing procedures employed in the emerging technologies docket to this proceeding. However, the Commission may need to develop mechanisms for sharing relocation costs between MSS providers if the movement of an incumbent benefits more than one MSS licensee. For example, if the lowest BAS channel is moved, thus clearing 18 MHz of spectrum, and more than one MSS licensee is assigned to this band, then all of these licensees should share in the cost of such a move. Similarly, the pairing of the terrestrial microwave links in the 2110-2150 MHz and 2160-2200 MHz bands may result in different MSS licensees benefiting from the relocation of fixed microwave stations. Therefore, the Commission must develop cost sharing mechanisms among MSS licensees as well.

V. THE COMMISSION DOES NOT NEED TO CONSIDER MSS FEEDER LINK ISSUES IN THIS PROCEEDING

The Commission asks whether there is a need to allocate spectrum for feeder links to support 2 GHz MSS systems. See NPRM at ¶ 16. While additional feeder links spectrum will be needed to accommodate additional MSS systems as they are developed and come into service, such additional allocations are already being considered in other domestic and international proceedings.

For example, the Commission is addressing the availability of MSS feeder links in the LMDS/FSS 28 GHz band proceeding,[35] and in its preparation for the upcoming WRC-95.[36] The WRC-95 agenda provides the United States with the opportunity to consider fully allocations and regulatory aspects of feeder links for MSS in the 1 to 3 GHz bands. See WRC-95 Agenda Item 2.1(c). Indeed, the CPM Report contains an extensive discussion under this agenda item, including estimated feeder link requirements for non-GSO MSS first-generation systems of 200 to 400 MHz in each direction in each of the 4-8 GHz and 8-16 GHz

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[35] See Rulemaking to Amend Part 1 and Part 21 of the Commission's Rules to Redesignate the 27.5-29.5 GHz Frequency Band and to Establish Rules and Policies for Local Multipoint Distribution Service, Second Notice of Proposed Rulemaking, 9 FCC Rcd. 1394 (1994).

[36] See In the Matter of Preparation for International Telecommunication Union World Radiocommunication Conferences, 9 FCC Rcd. 2430 (1994) ("Notice of Inquiry"); Second Notice of Inquiry, IC Docket No. 94-31, FCC 95-36 (rel. Jan. 31, 1995).

ranges, as well as 200 to 500 MHz in each direction in the 16-30 GHz range.[37]

Accordingly, the Commission should await the outcome of WRC-95 before considering additional MSS feeder link allocations.

VI. IT IS PREMATURE TO CONSIDER METHODS FOR ASSIGNING NEW MSS SPECTRUM AT 2 GHz TO SYSTEM OPERATORS

A. Auctions Are Inappropriate for Global Satellite Systems

As Motorola has consistently maintained in other proceedings, auctions are inappropriate for global satellite systems. Competitive bidding would in all likelihood lead to other countries following the lead of the United States and auctioning their MSS spectrum. Global U.S. MSS systems would therefore have to pay many other countries in addition to the United States for the right to use this spectrum.

Such an unfortunate precedent would also create the opportunity for payment schemes in other countries that could be used to discriminate against U.S. systems. Discrimination against U.S. systems in foreign jurisdictions is likely because systems licensed in the United States will be competing against systems licensed by other countries, including systems offered by foreign governments themselves. Indeed, then Chairman Quello identified

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[37] See CPM Report, ch. 2., sec. I., pt. C, para. 1.2.

the potential for discrimination in a letter to several Congressmen, wherein he urged that Congress should:

> ... be mindful of the potential ramifications [of spectrum auctions] on the international telecommunications service providers who utilize spectrum in other countries as well as in the United States. For example, requiring use of competitive bidding for low earth orbiting satellite system licenses in this country might subject those licensees to exorbitant payment requirements for access to spectrum in other countries. I am particularly concerned that some foreign governments opposed to the use of our international accounting and auditing standards could use our competitive bidding requirement as a justification for retaliatory measures.[38]

In addition, if competitive bidding were used, it would be virtually impossible to determine the value of a U.S. license at the time an auction was conducted due to the global nature of the services and the extensive international coordination that must take place on a bilateral basis. Big LEO systems, unlike terrestrial Personal Communications Service ("PCS") systems, will require licenses in most foreign countries and will be subject to many coordination agreements before service can be provided internationally. Moreover, given the large costs that new MSS systems must incur up front to construct and launch, requiring them to pay for spectrum both in the United States and abroad may impose a financial burden that some global MSS systems may not be able to bear. Unless and until the reciprocal bilateral arrangements that the Commission identified in the Big LEO MSS Licensing Order are negotiated on a country-by-country basis, such

[38] Letter from Chairman James H. Quello (June 23, 1993).

a combination of events would clearly place U.S. systems at a serious competitive disadvantage vis-à-vis foreign systems as well as jeopardize the technological leadership of the United States in important satellite and mobile communications. U.S. systems will also be competitively disadvantaged in the global MSS marketplace if Inmarsat-P or other foreign MSS systems are allowed to enter the U.S. market without having to pay for spectrum while U.S. licensed systems would be subject to auctions.

B. The Commission Is Required to Consider Other Licensing Alternatives Before Using Auctions

Title VI of the 1993 Omnibus Budget Reconciliation Act empowers the Commission to use competitive bidding only when mutually exclusive applications are accepted for filing for any initial license or construction permit. See 47 U.S.C. § 309(j)(1)(Supp. V 1993). The Act emphasizes that the Commission shall not be relieved of its "obligation in the public interest to continue to use engineering solutions, negotiation, threshold qualifications, service regulations, and other means in order to avoid mutual exclusivity in application and licensing proceedings...." 47 U.S.C. § 309(j)(6)(E). As the Chairman of the Commerce Committee of the House of Representatives stated in his letter to then Commission Chairman Quello,

> As a general proposition, by granting to the Commission the authority to assign licenses by auction, it was never the intent of Congress for auctions to replace the Commission's responsibilities to make decisions that are in the public interest. Rather, the competitive bidding authority was

> always intended to address those situations where the Commission could not either narrow the field of applicants or select between applicants based upon substantive policy considerations.
>
> * * * *
>
> To underscore that auctions are not a substitute for reasoned decision-making, the new statute specifies (at Section 309(j)(6)(E)) that the Commission is not to abandon its traditional methods of avoiding mutual exclusivity.[39]

The Commission has recently demonstrated its ability to assign limited amounts of spectrum without using auctions in the Big LEO proceedings. Here, as there, the Commission should use engineering solutions, negotiation, threshold qualifications, service regulations, and other means in order to avoid mutual exclusivity, thereby also avoiding the need to resort to auctions in this proceeding.

VII. CONCLUSION

The Commission should be applauded for its proposals to allocate an additional 70 MHz of global MSS spectrum in the United States and to attempt to convince the rest of the world to adopt similar allocations at WRC-95. There is an ever growing demand for global MSS spectrum, and the 2 GHz band represents the best near-term opportunity to make such spectrum available. While

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[39] Letter from John D. Dingell, Chairman, House Committee on Energy and Commerce, to James H. Quello (Nov. 15, 1993).

there still remains several important questions which must be addressed in this proceeding, the Commission appears to be well on its way toward allocating much needed MSS spectrum both domestically and internationally. Accordingly, Motorola urges the Commission to adopt its proposed MSS allocations in the 2 GHz band.

Respectfully submitted,

MOTOROLA, INC.

Philip L. Malet
Alfred Mamlet
Pantelis Michalopoulos
Miguel S. Lawson
Pamela Strauss
Steptoe & Johnson
1330 Connecticut Ave., N.W.
Washington, D.C. 20036
(202) 429-3000

Its Attorneys

Michael D. Kennedy
Vice President and Director,
Regulatory Relations
Stuart E. Overby
Assistant Director,
Spectrum Planning
Barry Lambergman
Manager, Satellite
Regulatory Affairs
Motorola, Inc.
1350 I Street, N.W.
Washington, D.C. 20005
(202) 371-6900

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APPENDIX I

Total Capacity in a Shared CDMA LEOS Environment

By

Vojcic, Milstein, Pickholtz

Total Capacity in a Shared CDMA LEOS Environment

Branimir R. Vojcic, *Member, IEEE*, Laurence B. Milstein, *Fellow, IEEE*, and Raymond L. Pickholtz, *Fellow, IEEE*

***Abstract*— We are interested in determining the feasibility of having multiple service providers share the same spectrum in transponder-type, satellite-based, code-division multiple-access mobile communications. To accomplish this, we compare the total capacity when n systems are operational to that when only a single system uses the frequency band. This comparison is made for both the uplink and the downlink under one of two possible constraints, either a maximum power flux density (PFD) limit per system, or an aggregate PFD limitation. While there are circumstances when the total capacity of multiple systems can achieve a greater value than that of a single service provider, conditions depend on the degree of shadowing, and whether or not the PFD limit is on a per system basis or on an aggregate basis from all systems.**

I. Introduction

It has been suggested that multiple satellite-based CDMA systems for mobile communications can co-exist in the same frequency band. In this paper, we quantify the total capacity achievable by having n separate service providers all share the same frequency band, and compare that capacity to what is achievable if only a single satellite system operates in the band. This comparison is done under one of two possible constraints, either a maximum received power flux density limit per system, or a power flux density limit on the aggregate received energy from all systems. Since the object here is comparison, no voice activity or other capacity enhancing mechanisms which can be applied in either case are considered.

In analyzing this problem, we rely heavily on the results of [1] and [2]. From [1], we make use of expressions for the ratio of signal-to-noise-plus-interference as a performance measure, with the implication that the use of such ratios is meaningful because they translate reasonably accurately to an estimate of average probability of error for a large number of simultaneously active CDMA waveforms. (This is typically not the case on the downlink because of correlated shadowing/fading among the transmitted signals.) We also use the model of [2], which assumes that when a mobile is shadowed, and thus experiences increased Rayleigh fading (see [3]), it is desirable to guarantee acceptable performance of that user by boosting its transmitted power by some amount greater than what is needed just to compensate for the shadow loss. More specifically, because of the relatively large round trip time delay that signals experience on low earth orbiting satellite (LEOS) links, closed loop power control is not very effective, and hence the rapid changes in signal power due to the Rayleigh fading caused by shadowing [3] cannot be tracked out. Therefore, some degree of power margin, P, must be provided in order to ensure that shadowed users do not experience an unacceptably large percentage of outages. This power margin can be applied so that shadowed users achieve the same average probability of error as the unshadowed users, or, with a smaller margin, that shadowed users realize some degraded, but still acceptable, performance [2].

International agreements on the operation of satellite communication downlinks have been made to protect terrestrial, fixed, line-of-sight microwave systems which share the same frequency band [4], [5] as the satellite system in question. These radio regulations specify a so-called "coordination trigger level" on the downlink power flux density (in dBW/m^2/4 kHz) from each satellite. That is, when the PFD reaches a certain limit, the regulations require coordination between the satellite and terrestrial systems. Because the coordination between fixed terrestrial services and LEOS systems is not possible due to the mobile nature of the latter, these trigger levels limit the amount of power flux density that a satellite transmitter may illuminate the earth in an unobstructed area. As such, they essentially impose a power limited operation onto LEOS systems, with corresponding consequences on their system capacities. The regulations, originally adopted by CCIR (now called ITU-R) over two decades ago for protection of terrestrial microwave systems against geosynchronous earth orbit satellites (GEOS), have been recently modified at WARC'92 [4]. Specifically, for the frequency band 2483.5–2500 MHz, which is allocated for downlinks of mobile satellite services and regulated by ITU regulation RR2566, WARC'92 set in Footnote 753F a coordination trigger of −142 dBW/m^2/4 kHz (previously −144 dBW/m^2/4 kHz), and a lower PFD level for low elevation angles. However, the operational scenario of multiple LEOS systems that share the same frequency band is different from that of GEOS, in that several LEO satellites can be in the main beam of the antenna of a fixed terrestrial microwave link. In that case, the specified PFD limit on a per satellite basis may not be adequate protection for terrestrial links. Indeed, if the interference protection is the objective

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B. R. Vojcic and R. L. Pickholtz are with the Department of Electrical Engineering and Computer Science, The George Washington University, Washington, DC 20052 USA.

L. B. Milstein is with the Department of Electrical and Computer Engineering, University of California at San Diego, La Jolla, CA 92093 USA.

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of PFD limits, it would appear that a PFD limit from the aggregate of *all* satellites in view ought to be the operational criterion.

There are no equivalent formal radio regulations for the uplink, i.e., limits on the total irradiance from, say, one square kilometer on the ground, designed to protect the satellite receiver, although several such proposals [6] have been made recently. Similar questions about per system versus aggregate uplink PFD limits need to be addressed.

We assume throughout this work that the constraint on power flux density can be mapped into an equivalent constraint on average power, and we denote this latter constraint by $P_{\max}$. Further, since, when only a single satellite system is operational, the number of users per spot beam per satellite, denoted by K_1, is directly proportional to that power constraint (ignoring other constraints such as one on peak transmit power), we present our results in terms of K_1.

We consider two scenarios, first, where only a single satellite from each one of n satellite systems (i.e., n service providers) illuminates a given mobile on the ground (which, of course, "belongs" to only one of those n systems), and second, where each of the n systems employ dual satellite diversity. In this latter case, each mobile is simultaneously illuminated by two satellites from each satellite system.

The paper is organized as follows. Section II presents the analysis of the uplink, while Sections III and IV are concerned with the downlink, all for the case of no diversity. The downlink results are then extended in Section V to incorporate the effects of dual satellite diversity. Section VI presents numerical results, and conclusions are given in Section VII.

II. Analysis of Uplink

It is desired to analyze the effect of multiple CDMA satellite systems operating under the constraint of either a PFD limit per system, or an aggregate limit on the total allowed PFD due to all systems combined. Toward that end, consider first the uplink, assume there are J spot beams per satellite, and assume that each system operates with the same number of users per spot beam. If we denote the signal-to-noise-plus-interference ratio of a given user in one satellite system, operating in the presence of $n-1$ other systems, by SNR_n, and if no mobile from any of the n systems is experiencing shadowing, then, under the conditions of coordinated perfect power control in all systems, we have from [1]

$$\mathrm{SNR}_n = \frac{1}{\frac{N_0}{2E_n} + n\frac{K_n I_0}{2L}}. \tag{1}$$

where $\frac{E_n}{N_0}$ is the energy-per-bit-to-noise spectral density ratio of a single user, K_n is the number of users per spot beam per system, L is the processing gain, and I_0 is the ratio of the total multiple-access interference that a user in a given spot beam experiences due to all spot beams in its own satellite system to the interference the user experiences only from its own spot beam ([1]). In essence, (1) says that every signal, from every satellite system, arrives at the satellite of the user-of-interest at the same power level.

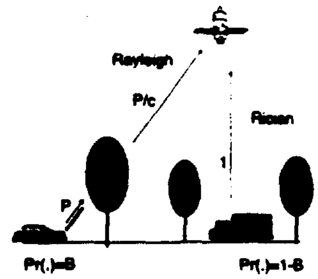

Fig. 1. Single system uplink shadowing scenario.

A. Single System with Shadowing

Assume now that the receive power levels of shadowed and nonshadowed users are unequal, even in the presence of perfect power control (see [2]). In other words, assume that a shadowed user is given a power advantage to compensate for the increased fading due to the shadowing ([2], [3]). Then, if B is the probability of a given user being shadowed (assumed the same for all users of all systems), it is shown in [2] that, for a single satellite system

$$\mathrm{SNR}_1 = \frac{1}{\frac{N_0}{2E_1} + \frac{K_1 I_0}{2L}\left(1 - B + \frac{B}{c}P\right)} \tag{2}$$

where

$$P = \frac{cX_s}{X_{ns}}. \tag{3}$$

c is the ratio of the nonshadowed specular power to the power in the shadowed signal (i.e., the shadowing loss), and X_s and X_{ns} are the signal-to-noise ratios (SNR's) in the scattered and nonscattered cases, respectively, which are required to yield the desired performance. The parameter P is a power amplification that is applied to shadowed users (and which are thus in a faded state), in order to ensure that their performance is the same as that of an unshadowed user [2], [7]. Stated differently, BP/c corresponds to a shadowed user's contribution to the multiple-access interference (see [2] for a more detailed explanation of the model).

Note that for a single system, there is only one PFD limit, and we have a constraint of the form

$$I_0 K_1 P_1 A_1 \leq P_{\max} \tag{4}$$

where $P_{\max}$ is the power constraint, P_n is the average power per user when n systems are simultaneously operational, and A_1 is a factor which takes into account the excess power of a shadowed user as compared to an unshadowed user (see Fig. 1). It is defined as

$$A_1 \triangleq 1 - B + \frac{B}{c}P \tag{5}$$

and simply says that with $100 \times B$ percent of users shadowed, the average received power, relative to a unit power for a nonshadowed signal, is $(1-B)(1) + \frac{BP}{c}$, where the second term corresponds to a shadowed signal experiencing both an attenuation of c and a power boost of P.

For future use, we define $K_{1,\infty}$ to be the maximum capacity of a single system, corresponding to $\frac{E_1}{N_0} \to \infty$. From (2), we see that

$$K_{1,\infty} = \frac{2L}{I_0 A_1(\mathrm{SNR}_1)}. \tag{6}$$

B. Multiple Systems with Shadowing

Now consider n satellite systems sharing the same total bandwidth, each with processing gain L. Analogous to (2), it is straightforward to show that SNR_n is given by

$$\mathrm{SNR}_n = \frac{1}{\frac{N_0}{2E_1} + \frac{K_1 I_0}{2L}A_1 + E(I^2)} \tag{7}$$

where I is defined to be the interference seen by the user-of-interest due to mobiles belonging to all of the other $n-1$ satellite systems. To compute $E[I^2]$, note that there are four distinct situations which can arise (depicted in Fig. 2): the interfering user on the ground can be shadowed both to its own satellite as well as to the satellite-of-interest, the interfering user can be shadowed to neither satellite, or it can be shadowed to one, but not to both of the satellites. Realizing that a user shadowed to its own satellite has its power augmented by the factor P defined by (3), that a user shadowed to the satellite-of-interest has its power attenuated by the factor c (note that these are not mutually exclusive events), and that the probability of the interfering user being shadowed to one satellite is taken to be independent of the probability of it being shadowed to any other satellite, we have for the second moment of I (see also [8])

$$\begin{aligned} E[I^2] &= \frac{(n-1)KI_0}{2L} \\ &\quad \times \left[\frac{P}{c}B^2 + PB(1-B) + \frac{1}{c}(1-B)B + (1-B)^2\right] \\ &= \frac{(n-1)K_n I_0}{2L}A_2 A_3 \end{aligned} \tag{8}$$

where

$$A_2 \triangleq 1 - B + PB \tag{9}$$

and

$$A_3 \triangleq 1 - B + \frac{B}{c}. \tag{10}$$

Note that $A_2 \geq 1$ and $A_3 \leq 1$; note further that A_2 corresponds to a user shadowed to its own satellite but not to the victim satellite, whereas A_3 corresponds to a user with a clear path to its own satellite but with a shadowed path to the victim satellite.

For the n satellite-system case, we have to consider separately the PFD limit per system and the aggregate PFD limit. In the former case, we have

$$I_0 K_n P_n A_2 A_3 \leq P_{\max} \tag{11}$$

where we define the PFD as that imposed on any one system by any of the remaining $n-1$ systems. If we assume that in both (4) and (11) the equality sign holds, we see that

$$P_n = \frac{K_1}{K_n}\frac{A_1}{A_2 A_3}P_1. \tag{12}$$

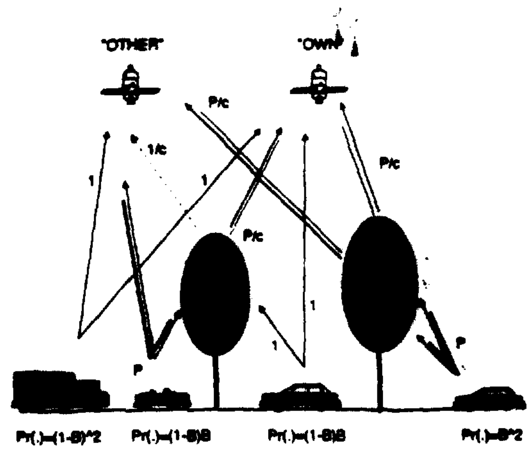

Fig. 2. Multiple systems uplink shadowing scenario.

Therefore, upon setting

$$\mathrm{SNR}_1 = \mathrm{SNR}_n \tag{13}$$

that is, upon demanding that the performance of a given user in a single service provider system be the same as when n service providers coexist, we have from (2), (7), and (12)

$$\frac{nK_n}{K_1} = \frac{1}{A\left\{\frac{1}{n} + \frac{K_1}{K_{1,\infty}}\left[1 - \frac{1}{n}\left(2 - \frac{1}{A}\right)\right]\right\}} \tag{14}$$

where

$$A \triangleq \frac{A_2 A_3}{A_1}. \tag{15}$$

It should be noted that $A > 1$ when $B > 0$; it should also be noted that the net effect of fading caused by the shadowing is a degradation in performance, since the increase in MAI because of other users compensating for shadowing in their systems outweighs the power increase in the system-of-interest due to its own shadowing. With no shadowing, $B = 0$ and $A = 1$.

C. Comparison of Single and Multiple Systems

It is of interest to know when the right-hand side of (14) exceeds unity. That is, it is of interest to know when the total capacity of n service providers exceeds that of a single service provider. For the denominator of (14) to be less than unity, we have[1]

$$n > \frac{1 - \left(2 - \frac{1}{A}\right)\frac{K_1}{K_{1,\infty}}}{\frac{1}{A} - \frac{K_1}{K_{1,\infty}}} \tag{16}$$

assuming that $\frac{1}{A} > \frac{K_1}{K_{1,\infty}}$. Note that if there was no shadowing in any system (and thus no fade compensation), $A = 1$, (16) reduces to $n > 1$, and the total capacity of n systems always exceeds that of a single system. When shadowing is present the result depends upon the specific value of A, which is a function of B, P, and c. Numerical results will be presented in Section IV.

[1] The normalized capacity, $K_1/K_{1,\infty}$, for a single system is monotonically related to the PFD limit by (11) and (12). The explicit relationship is derived in the Appendix for the downlink, together with a numerical example that is used in Section VI.

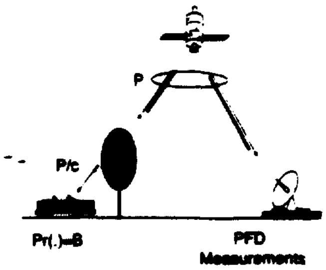

Fig. 3. Single system downlink shadowing and PFD measurement scenario.

Consider now the situation in which there is an aggregate PFD limit. For this case, we have

$$I_0 K_n P_n [A_1 + (n-1) A_2 A_3] \leq P_{max}. \tag{17}$$

Note that in this case, as opposed to (11), we define the PFD constraint to include all multiple-access interference, including that due to the system of interest. The first term in the brackets provides the excess fractional MAI power of the target system due to shadowing, while the second term gives the fractional excess power due to the remaining $n-1$ systems because of the four conditions of shadowing described above. Following the same reasoning as above, we have

$$P_n = \frac{P_1 K_1}{K_n[1+(n-1)A]} \tag{18}$$

and

$$\frac{nK_n}{K_1} = \frac{n}{1+(n-1)A}. \tag{19}$$

Note that from (19), $\frac{nK_n}{K_1} = 1$ if $A = 1$ (i.e., no shadowing). However, for $A > 1$, the right-hand side of (19) exceeding unity implies $n < 1$, so that, for an aggregate PFD limit on the uplink, a single service provider yields the highest net capacity.

III. Downlink Analysis

The analysis for the downlink is basically similar to that presented in Section II for the uplink. However, one important difference is that the PFD requirement has to be satisfied on the ground at an unshadowed location, as depicted in Fig. 3. This implies that the PFD limit on the downlink will be more constraining than its counterpart on the uplink. Further, the fading/shadowing experienced by signals emanating from a given satellite are invariably correlated, because they transverse a very similar path (although the analysis presented below, based on SNR considerations, is not affected by such correlation).

If we consider first a single system of satellites with nonorthogonal downlink CDMA signals, then the PFD requirement can be expressed as

$$K_1 P_1 I_0 A_2 \leq P_{max} \tag{20}$$

and the SNR at a mobile on the ground is given by

$$\mathrm{SNR}_1 = \frac{1}{\frac{N_0}{2E_1} + \frac{K_1 I_0}{2L} A_2}. \tag{21}$$

For multiple CDMA systems under a PFD limit per system, we have

$$K_n P_n I_0 A_2 \leq P_{max} \tag{22}$$

as the power constraint equation, and

$$\mathrm{SNR}_n = \frac{1}{\frac{N_0}{2E_n} + \frac{K_n I_0}{2L} A_2 + (n-1)\frac{K_n I_0}{2L} A_2 A_3}. \tag{23}$$

Thus, from (20), (22), and (23), we see that

$$\frac{nK_n}{K_1} = \frac{n}{1+(n-1)\frac{K_1}{K_{1,\infty}} A_3} \tag{24}$$

where now $K_{1,\infty}$ is obtained from (21) as

$$K_{1,\infty} = \frac{2L}{I_0 A_2 (\mathrm{SNR}_1)}. \tag{25}$$

Note that, analogous to the uplink, if no user in any system experiences any shadowing, then $A_3 = 1$, and for any $n > 1$, we have $nK_n > K_1$. On the other hand, we see from either (24) for the downlink or (14) for the uplink, that, in the absence of shadowing, as $n \to \infty$, $nK_n \to K_{1,\infty}$. In other words, on a purely Gaussian channel (i.e., no shadowing), the total capacity of n systems cannot exceed the maximum capacity of a single system. This last conclusion does not hold when shadowing is present, as can bee seen, for example, from (24). If $A_3 < 1$, (i.e., if $B > 0$), then as $n \to \infty$, $nK_n \to K_{1,\infty}/A_3$, which exceeds $K_{1,\infty}$.

For n CDMA systems operating with an aggregate PFD limit, we have[2]

$$nK_n P_n I_0 A_2 \leq P_{max} \tag{26}$$

and

$$\frac{nK_n}{K_1} = \frac{1}{1 - \frac{K_1}{K_{1,\infty}}(1-A_3)\frac{n-1}{n}}. \tag{27}$$

From (27), clearly $K_1 = nK_n$ when $A_3 = 1$; when $A_3 < 1$, $nK_n > K_1$ for any $n > 1$, and so for the downlink, n systems always yield a greater capacity than does a single system.

As a final perspective, consider a situation whereby we remove the PFD limit on the ground and determine how much additional power must be transmitted per user in a single service provider system to yield a capacity greater than that of an n server provider system. That is, let the energy-per-bit of a user when there are n CDMA satellite systems be E, and let the energy-per-bit in a single system be mE, for some m. Then

$$\mathrm{SNR}_1 = \frac{1}{\frac{N_0}{2mE} + \frac{K_1 I_0 A_2}{2L}} \tag{28}$$

and

$$\mathrm{SNR}_1 = \frac{1}{\frac{N_0}{2E_1} + \frac{K_1 I_0 A_2}{2L} + (n-1)\frac{K_n I_0 A_2 A_3}{2L}}. \tag{29}$$

[2] In contrast to (17), the ground PFD limit is always measured at a nonshadowed point.

Solving for the ratio $\frac{nK_n}{K_1}$, we obtain

$$\frac{nK_n}{K_1} = \frac{n\left[1 - m\left(1 - \frac{K_1}{K_{1,\infty}}\right)\right]}{\frac{K_1}{K_{1,\infty}}[1 + (n-1)A_3]}. \tag{30}$$

For K_1 to exceed nK_n, we need

$$m > \frac{1 - \frac{K_1}{K_{1,\infty}}\left[\frac{1}{n} + \left(1 - \frac{1}{n}\right)A_3\right]}{1 - \frac{K_1}{K_{1,\infty}}}. \tag{31}$$

Note that for $A_3 = 1$ (no shadowing), any $m > 1$ results in $K_1 > nK_n$. This emphasizes that for no shadowing on the downlink, the increase in total capacity is achieved in multiple systems only because a PFD limit prevents a single system from achieving capacity. Note that m may also be interpreted as an economic factor by which we can compare a single system versus multiple systems with the same capacity. That is, one can use m to tradeoff the costs of increasing the transmit power in a single system versus deploying multiple systems with a lower transmit power. For $A_3 < 1$, the results depend on specific parameters chosen, just as in the cases where a PFD limit was imposed, and numerical results are presented in Section VI. As will be seen, the existence of shadowing actually helps (somewhat) in multiple systems.

IV. Downlink with Orthogonal Sequences

The downlink results obtained to this point are pessimistic, in that they do not take advantage of the orthogonality between spreading sequences which is typically employed on the forward links. That is, by employing orthogonal spreading, the amount of multiple-access interference can be reduced, depending upon the degree of the orthogonality that is achievable for the given bandwidth. That would enable the use of a smaller transmit power per user and, for a given PFD limit, would contribute to an increase of the system capacity.

A. Full-Orthogonality Case

In the most optimistic case, the processing gain is sufficiently large, so that every signal from every spot beam of the satellite is orthogonal to all another signals. This implies that $JK_1 \leq L$. Then

$$\mathrm{SNR}_1 = \frac{2E_1}{N_0}. \tag{32}$$

Since, in the multiple service providers case, the orthogonality cannot be maintained with signals from other satellites, because of varying propagation delays, the composite downlink SNR is given by

$$\mathrm{SNR}_n = \frac{1}{\frac{N_0}{2E_n} + (n-1)\frac{K_n I_0}{2L}A_2A_3}. \tag{33}$$

From (22) and (32)–(33), one can obtain, for a PFD limit per system

$$\frac{nK_n}{K_1} = \frac{n}{1 + (n-1)\frac{K_1}{L}\frac{I_0(\mathrm{SNR})A_2A_3}{2}}. \tag{34}$$

It can be seen from (34) than $nK_n > K_1$ for any $n > 1$, whenever $K_1/L < 2/[I_0(\mathrm{SNR})A_2A_3]$. Otherwise, if $K_1/L > 2/[I_0(\mathrm{SNR})A_2A_3]$, a single system achieves the maximum capacity. When an aggregate PFD limit is imposed, it follows from (26) and (32)–(33) that

$$\frac{nK_n}{K_1} = \frac{1}{1 + \left(1 - \frac{1}{n}\right)\frac{K_1}{L}\frac{I_0(\mathrm{SNR})A_2A_3}{2}}. \tag{35}$$

It is easy to see from (35) that for any $n > 1$, $nK_n < K_1$, for all possible values of other system parameters. That is, with an aggregate PFD limit, a single system provider always outperforms multiple systems with respect to achievable capacity.

B. Arbitrary Degree of Orthogonality

The assumption that all signals from a given satellite are orthogonal is typically unrealistic, since it would imply too large a processing gain. Therefore, we consider in this subsection more limited cases of orthogonality. Note that the comparison of the performance of n service providers with that of a single service provider has multiple facets to it. For example, suppose a single service provider system is such that $K_1 = L$, so that orthogonality exists only within a given spot beam. For an n service provider scenario, we assume that each satellite of each system has the same processing gain as does a satellite when only a single service provider exists, but K_n, the number of users per spot beam when n systems coexist, is less than the analogous quantity for a single system, namely K_1. Therefore, if $K_1 = L$, then $K_n < L$, and additional orthogonality can be used to advantage when $n > 1$.

To gain a perspective on the effect of orthogonality, consider the following possibilities for a single system. If $JK_1 > L$, we have

$$\mathrm{SNR}_1 = \frac{1}{\frac{N_0}{2E_1} + \frac{K_1 I_1}{2L}A_2} \tag{36a}$$

where $0 < I_1 < I_0$. When $K_1 = L$, then

$$\mathrm{SNR}_1 = \frac{1}{\frac{N_0}{2E_1} + \frac{(I_0 - 1)}{2}A_2}. \tag{36b}$$

More specifically, when $JK_1 > L$ and $K_1 < L$, then (36a) applies with $0 < I_1 < I_0 - 1$, and when $K_1 > L$, then (36a) again applies, but now $I_0 - 1 < I_1 < I_0$. Note that, for future reference, if we define $I_{1,\infty}$ to be the value of I_1 when $\frac{E_1}{N_0} \to \infty$, then we have

$$K_{1,\infty} = \frac{2L}{I_{1,\infty}A_2\mathrm{SNR}_1}. \tag{37}$$

From (37), we see that $K_{1,\infty}$ depends upon the system design parameters L and SNR, and on the amount of shadowing in the systems, which is reflected by A_2. Also, $I_{1,\infty}$ is implicitly a function of $K_{1,\infty}$. For example, if we assume that $K_{1,\infty} > L$ then $I_{1,\infty} = I_0 - \frac{L}{K_{1,\infty}}$ and (37) reduces to

$$K_{1,\infty} = \frac{L}{I_0}\left(1 + \frac{2}{A_2\mathrm{SNR}_1}\right). \tag{38}$$

To ensure that $K_{1,\infty} > L$, from (38), A_2 must satisfy

$$A_2 < \frac{2}{\mathrm{SNR}_1}(I_0 - 1). \tag{39}$$

However, recall from (9) that $A_2 \geq 1$, and thus (39) is very unlikely to be satisfied. Equivalently, we must have

$$B < \frac{1}{P-1}\left[\frac{2}{\mathrm{SNR}_1(I_0-1)} - 1\right] \quad (40)$$

which indicates that the percent shadowing and the acceptable SNR are both small. On the other hand, if (39) is not satisfied, $K_{1,\infty} < L$ and can be bounded by

$$\frac{2L}{(I_0-1)A_2\mathrm{SNR}_1} < K_{1,\infty} < L. \quad (41)$$

In (41), the left-hand inequality follows from (37) by noting that $I_0 - 1 \leq I_1 < I_{1,\infty}$.

We now consider n simultaneously operational systems, and reiterate that, because $K_n < K_1$, then $I_n < I_1$. The composite downlink SNR is given by

$$\mathrm{SNR}_n = \frac{1}{\frac{N_0}{2E_n} + \frac{K_n I_n}{2L}A_2 + (n-1)\frac{K_n I_0}{2L}A_2 A_3}. \quad (42)$$

If we have a PFD limit per system, then, using the same conditions for the downlink as in the previous section, we have

$$\frac{nK_n}{K_1} = \frac{n}{1 + \left\{\frac{K_1}{K_{1,\infty}}[(n-1)I_0A_3 + I_n]\frac{1}{I_{1,\infty}} - \frac{I_1}{I_{1,\infty}}\right\}}. \quad (43)$$

From (43), it can be shown that $nK_n > K_1$ for any $n > 1$ if either $K_1/K_{1,\infty} < I_{1,\infty}/I_0A_3$ or

$$n < 1 - \frac{I_1 - I_n}{\frac{K_{1,\infty}I_{1,\infty}}{K_1} - I_0A_3} \text{ and } \frac{K_1}{K_{1,\infty}} \geq \frac{I_{1,\infty}}{I_0A_3}. \quad (44)$$

When we have an aggregate PFD limit, then

$$\frac{nK_n}{K_1} = \frac{1}{1 + \frac{K_1}{I_{1,\infty}K_{1,\infty}}\left\{\frac{1}{n}[(n-1)I_0A_3 + I_n] - I_1\right\}} \quad (45)$$

and a single service provider always yields a greater capacity as long as

$$I_1 < \left(1 - \frac{1}{n}\right)I_0A_3 + \frac{I_n}{n}. \quad (46)$$

Note that (46) is satisfied for values of n defined by

$$n\frac{I_0A_3 - I_n}{I_0A_3 - I_1} \text{ and } A_3 < \frac{I_1}{I_0} \quad (47a)$$

or

$$n < \frac{I_0A_3 - I_n}{I_0A_3 - I_1} \text{ and } A_3 > \frac{I_1}{I_0}. \quad (47b)$$

Suppose now, for both the single system and multiple systems, orthogonality is only maintained within each spot beam of each satellite, whereas the spreading waveforms belonging to different spot beams are not mutually orthogonal. Equation (36b) gives the SNR for $n = 1$, and SNR_n is given by

$$\mathrm{SNR}_n = \frac{1}{\frac{N_0}{2E_n} + \frac{K_n(I_0-1)}{2L}A_2 + (n-1)\frac{K_n I_0}{2L}A_2A_3}. \quad (48)$$

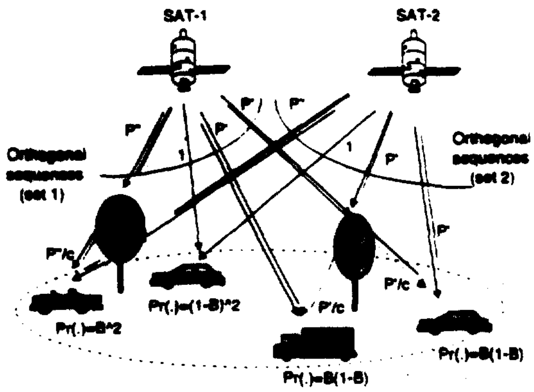

Fig. 4. Single system downlink scenario for dual-diversity.

If the PFD is on a per system basis, then it can be shown that n systems always outperform a single system if

$$K_1 < \frac{2L}{I_0A_2A_3\mathrm{SNR}_1} \quad (49)$$

otherwise, a single system achieves maximum capacity.

For an aggregate PFD limit, if $A_3 > 1 - \frac{1}{I_0}$, then maximum capacity is achieved for $n = 1$. If the inequality is reversed, then $n > 1$ is optimal.

V. Performance in the Presence of Dual Satellite Diversity

In this section, we extend the previous results by incorporating dual satellite diversity in the model. That is, we assume that each mobile is always in sight of two satellites from each system. For brevity, we concentrate only on the down-link, and we assume that the difference in arrival times of the signals from the two satellites transmitting to any given mobile is greater than the duration of one chip of the spreading sequence, so that a RAKE receiver can be employed by the mobile.

Consider first a single service provider. The corresponding communication scenario is shown in Fig. 4. It should be noted that the orthogonality cannot be maintained between the signal waveforms belonging to different satellites of the same system due to different and variable propagation delays to any given mobile.

By extending the results of the previous section, it is straightforward to show that if the spreading sequences are such that all sequences within a given spot beam are orthogonal, then the output of a maximal-ratio combiner at the mobile receiver has a SNR given by

$$\mathrm{SNR}_1 = \frac{2}{\frac{N_0}{2E_1} + \frac{K_1(2I_0-1)\gamma}{2L}} \quad (50)$$

where, as can be seen from Fig. 4

$$\gamma = (1-B)^2 + 2B(1-B)P' + B^2P''. \quad (51)$$

The parameters P' and P'' in (51) arise in the following manner: We assume that if a mobile is shadowed to both satellites from which it is receiving, each of those satellites increases its transmit power to that mobile by a factor of P''. If the mobile is shadowed to only one satellite, each

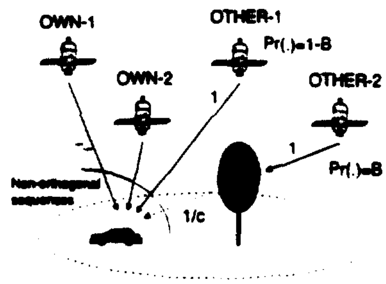

Fig. 5. Multiple systems downlink scenario for dual-diversity.

satellite boosts its power by a factor of P', and there is no power boost if the mobile has a clear line-of-sight path to both satellites. As an example, suppose that when a mobile is shadowed to a satellite, its power is attenuated by a factor $c > 1$. Then one possible set of values (P', P'') is $P' = 1$ and $P'' = c$, which corresponds to only boosting power when both satellites are shadowed. Another alternative would be to choose (P', P'') so as to provide the same bit-error-rate (BER) performance in all possible shadowing scenarios. To achieve that, we must have $P' > 1$ and $P'' > c$. In any event, for a given pair (P', P''), the parameter γ in (51) is the average power enhancement (or, equivalently, the multiple-access interference amplification factor), where the average is over the shadowing state of both satellites.

Suppose now that there are n systems simultaneously operational. The communication scenario for two systems, for simplicity, is shown in Fig. 5. It can be shown that the output SNR for n systems is given by

$$\mathrm{SNR}_n = \frac{2}{\frac{N_0}{2E_n} + \frac{K_n(2I_0-1)\gamma}{2L} + \frac{K_n I_0 \gamma A_3}{2L} 2(n-1)}. \tag{52}$$

Analogous to γ in (51), the product γA_3 in the third term of the denominator of (52) represents the average power enhancement due to different shadowing combinations of mobiles within any of the $n-1$ interfering systems and the mobile in the system-of-interest. That is, consider any satellite in one of the $n-1$ interfering systems. Its average power boost to its own mobiles is given by γ; however, the mobile in the system-of-interest may or may not be shadowed to that interfering satellite, and thus γ must be multiplied by A_3.

To compare the capacity of a single service provider with the total capacity of n service providers, it is necessary to include the PFD constraint. If we consider first a PFD limit imposed on a per satellite basis, we must satisfy the following condition

$$K_1 E_1 = K_n E_n. \tag{53}$$

Using (50), (52), and (53), we have, upon setting

$$\mathrm{SNR}_1 = \mathrm{SNR}_n = \mathrm{SNR} \tag{54}$$

$$\frac{nK_n}{K_1} = \frac{n}{1 + (n-1)\frac{K_1 I_0 \gamma A_3}{2L}\mathrm{SNR}}. \tag{55}$$

We are interested in the condition under which $nK_n > K_1$. From (55), that condition is given by

$$\frac{K_1}{L} < \frac{2}{I_0 \gamma A_3 (\mathrm{SNR})}. \tag{56}$$

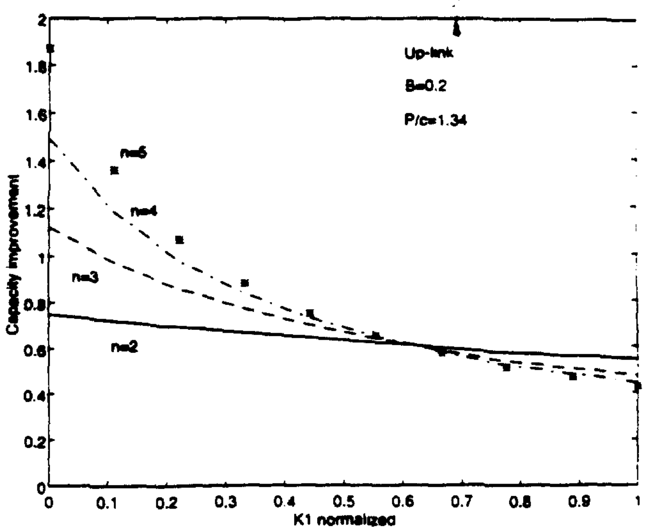

Fig. 6. Uplink capacity improvement due to spectrum sharing: PFD constraint on a per system basis.

For an aggregate PFD limitation, the constraint can be expressed as

$$K_1 E_1 = nK_n E_n. \tag{57}$$

Combining (50) and (52) with (57) now yields

$$\frac{nK_n}{K_1} = \frac{1}{1 + \frac{K_1 \gamma (\mathrm{SNR})}{2L}\left(\frac{n-1}{n}\right)\left[I_0 A_3 - \frac{2I_0 - 1}{2}\right]} \tag{58}$$

and the total capacity of n systems will exceed that of a single system when

$$A_3 < 1 - \frac{1}{2I_0}. \tag{59}$$

VI. Numerical Results

It was shown in Section II (see (19)) that, in the presence of shadowing, a single system always outperforms n systems when an aggregate PFD limit constrains the uplink. This is a consequence of the "near-far"[3] effect introduced by the power control mechanism to combat shadowing. The reason for the difference between this "near-far" effect for a single and multiple systems can be seen qualitatively in Figs. 1 and 2. When the signal of a shadowed user is amplified to neutralize the effects of shadowing and fading, it may propagate unobstructed toward satellites belonging to other systems, and thus cause excessive multiple-access interference. At any given satellite, this interference is proportional to the PFD as seen by that satellite. Since the aggregate PFD is limited, this effect results in the loss of capacity. Similarly, it can be shown that in the absence of any PFD limitation, a single system always achieves a larger capacity than multiple systems.

When the PFD limit is imposed on a per system basis, the ratio $\frac{nK_n}{K_1}$ (denoted "Capacity improvement") is plotted for

[3] There is no near-far effect in clear line-of-sight satellite communications in the sense that it exists in terrestrial spread spectrum systems. Here we use the term to denote simply the difference in received power levels which results from shadowing and power control.

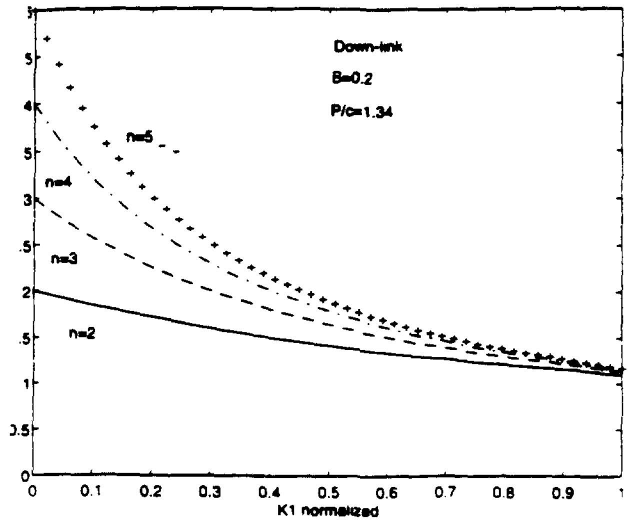

Fig. 7. Downlink capacity improvement due to spectrum sharing; PFD constraint on a per system basis.

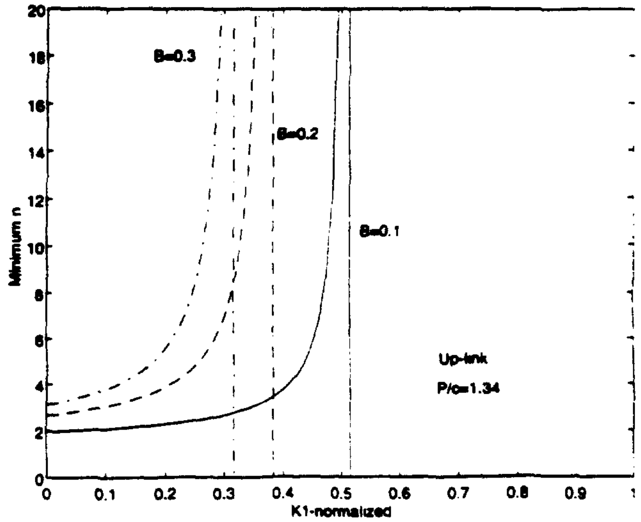

Fig. 9. Minimum required number of service providers to achieve capacity improvement for the uplink: PFD constraint on a persystem basis.

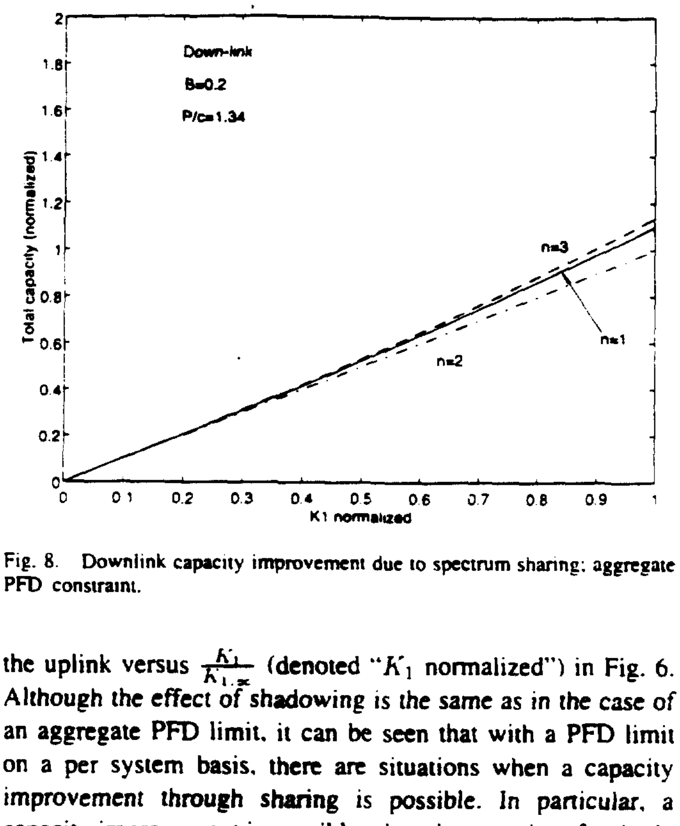

Fig. 8. Downlink capacity improvement due to spectrum sharing: aggregate PFD constraint.

the uplink versus $\frac{K_1}{K_{1,\infty}}$ (denoted "K_1 normalized") in Fig. 6. Although the effect of shadowing is the same as in the case of an aggregate PFD limit, it can be seen that with a PFD limit on a per system basis, there are situations when a capacity improvement through sharing is possible. In particular, a capacity improvement is possible when the capacity of a single system is relatively small to begin with, and when the number of service providers exceeds some number. It should be noted that this improvement is only possible because of constraining artificially a single system (by imposing on it a PFD limit) from achieving its full capacity. Fig. 7 shows similar results for the downlink; in this figure, the downlink sequences do not make use of orthogonality. When an aggregate PFD limit is imposed on the downlink under the same conditions as used for Fig. 7, the curves shown in Fig. 8 result.

It is of interest at this point to note that results for the downlink are fundamentally different from those of the uplink in that capacity improvement is always achieved by sharing on the downlink, although the "near–far" effect is present both links. The difference stems from the reference points at which the PFD's are measured. On the uplink, it is assumed that the PFD is measured above tree levels and, hence, it is directly proportional to the amount of multiple-access interference as seen by each of the satellites. On the downlink, however, the PFD is measured at a location which has a clear line-of-sight with all satellites which cover the geographical area of interest, and the capacity is primarily limited by the imposed PFD constraint. A specific mobile may be shadowed with respect to some of the other system providers' satellites, and, consequently, receive less multiple-access interference compared to what it would receive an unobstructed location. That, in turn, enables the use of a smaller average transmit power per user, which results in a reduction in PFD and, hence, an increase in the capacity. This explains also why the total maximum capacity of n systems exceeds the maximum capacity of a single system (corresponding to $E_b/N_0 \to \infty$), which can be seen from Figs. 7 and 8. It should be noted that the results in Fig. 7 do not account for the possibility of saturating the satellite transponders by increasing the number of systems and the aggregate PFD; this latter effect can result in an equivalent SNR degradation of 1 dB or more [9].

An alternate way to look at these results is to see how much increase in energy per user in a single system is needed to yield a capacity greater than that of n systems. Specifically, to determine by how much a single system, operating in the absence of a PFD limit, must increase the energy-per-bit of each user on the downlink over and above that used by a single subscriber when n systems coexist, consider Fig. 9. In this figure, for various values of n, the factor by which E_1 must be multiplied, m, is plotted versus $\frac{K}{K_{1,\infty}}$. It is seen that m is very close to unity for $\frac{K_1}{K_{1,\infty}}$ as large as 0.7. As pointed out earlier, the factor m can be interpreted as an economic factor which indicates the required increase in transmit power per satellite for a single system to achieve the same capacity as n systems. More importantly, if one is concerned with the total interference as seen by a fixed terrestrial microwave station,

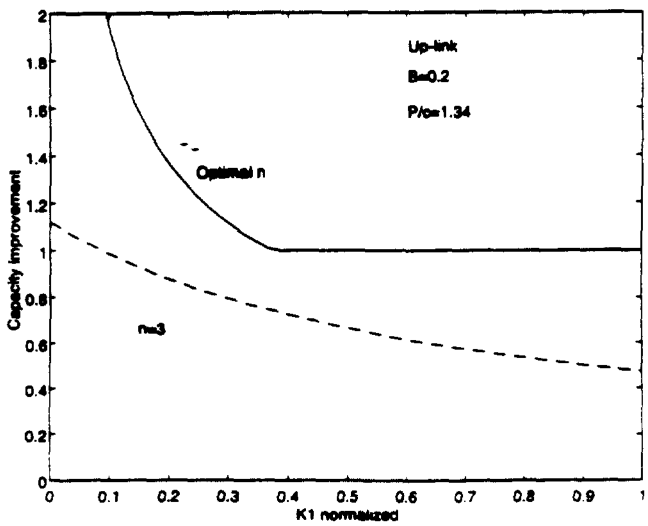

Fig. 10. Comparison of the capacity improvement for $n = 3$ and optimal number of service providers for the PFD constraint on a per system basis.

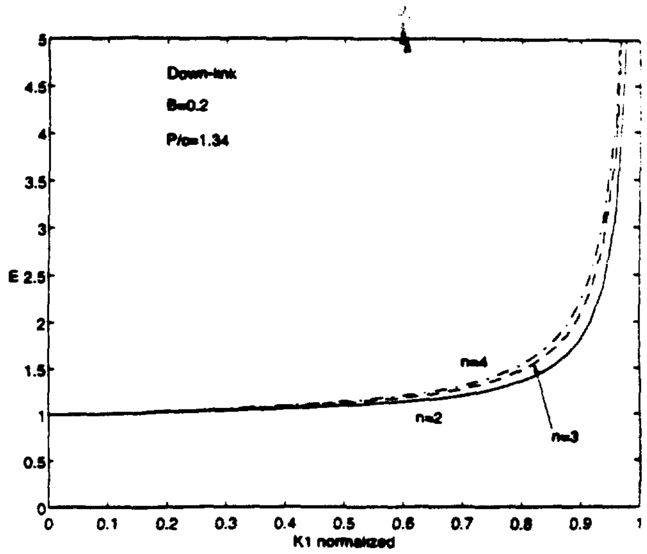

Fig. 12. PFD increase factor for a single system to achieve the same capacity as n systems.

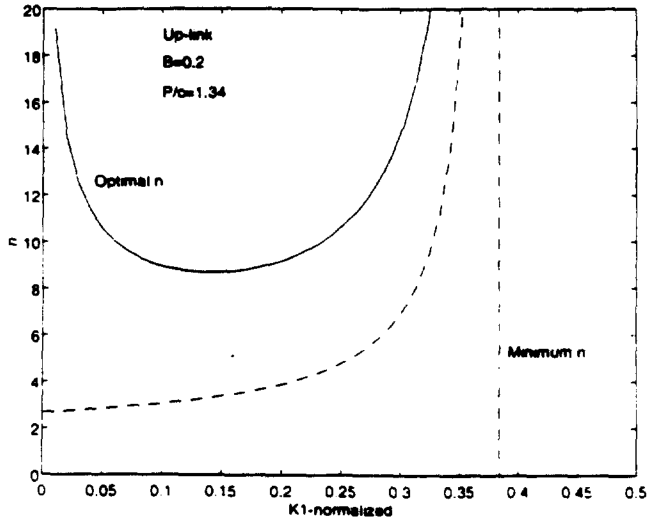

Fig. 11. Comparison of the optimal and minimum number of service providers to achieve a capacity improvement for the uplink: PFD constraint on a per system basis.

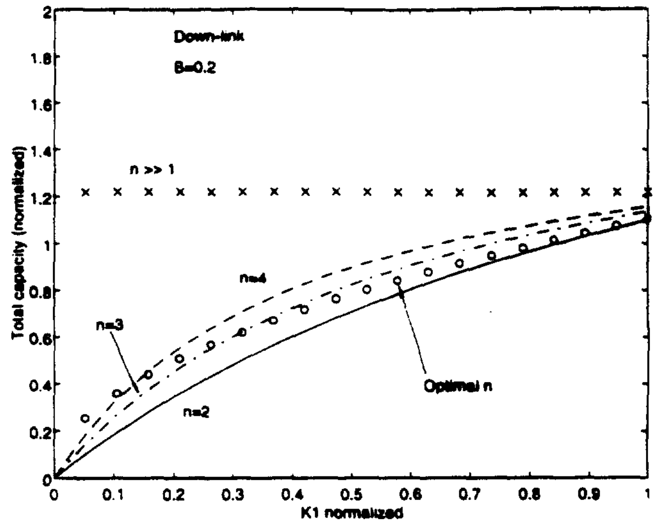

Fig. 13. Downlink total capacity for different values of the number of service providers: PFD constraint on a per system basis.

this factor m indicates the required increase in the PFD limit per satellite to achieve the same capacity as n systems with the original PFD limit. It can be concluded by considering the results of Fig. 9 that a single satellite would produce much less interference, for the same capacity as that of n systems, for almost the entire range of $K_1/K_{1,\infty}$. As an example, if a single system with a given PFD limit operates at 90% of its maximum capacity, it needs to increase that PFD by a factor of 2 to achieve the same capacity as four systems. That is, the same capacity is achieved while producing one-half the total interference to terrestrial systems.

To gain a somewhat different perspective on these results, consider Figs. 10–12. All three figures correspond to the uplink, and the curves are always plotted against $\frac{K_1}{K_{1,\infty}}$. In Fig. 10, the minimum value of n which results in $nK_n > K_1$ is presented with B, the percent shadowing, as a parameter. Three curves are shown, along with a vertical line associated with each curve; for $\frac{K_1}{K_{1,\infty}}$ to the right of the vertical line, $n = 1$ is optimum. For example, if we consider the curves corresponding to $B = 0.2$, we can revisit Fig. 6 to provide the following interpretation. On Fig. 6, the region where $n > 1$ yields greater capacity than does $n = 1$ corresponds to the upper lefthand quadrant bounded by the lines "capacity improvement" = 1 and "K_1 normalized" = 0.38.

In Fig. 11, the capacity improvement is shown for two situations, one corresponding to $n = 3$, and the other referred to as the "optimal n". This latter value corresponds to that n which maximizes the ratio $\frac{nK_n - K1}{n}$; that is, it maximizes the capacity increase per system when going from single to multiple service providers. Fig. 12 presents similar results from a somewhat different perspective; both the optimal value of n, as defined above, and the minimum value of n needed for n systems to outperform a single system, are plotted versus $\frac{K_1}{K_{1,\infty}}$.

In Fig. 13, we compare the capacity improvement over a single system for different values of n, where a per system

TABLE I
CHARACTERISTIC VALUES OF SYSTEM PARAMETERS

B	A_2	A_3	$K_{1,\infty}$	$I_{1,\infty}$	$(K_1/K_{1,\infty})_{\lim}$	$(K_1/L)_{\lim}$
0	1	1	1.1	1.12	0.552	[illegible]
0.014	1.21	[illegible]	1	1.02	0.551	0.551
0.122	2.83	[illegible]	0.5	0.87	0.484	0.242
0.276	5.14	0.75	0.33	0.72	0.474	0.158

PFD limit is imposed on the downlink. Specifically, we consider n very large ($n \to \infty$), which corresponds to the maximum achievable capacity of n systems, the optimal n, and $n = 3$ and 4. It can be seen that the optimal n in this case, for almost all values of $K_1/K_{1,\infty}$, is relatively small (less than or equal to 4).

Let us now examine the downlink performance with orthogonal spreading sequences. To obtain specific results, we assume that a nonshadowed user operates with an SNR of 2 dB. Assuming a data rate per user of 4.8 kbps and a spread bandwidth of 1.25 MHz, the processing gain per coded symbol is $L = 130$. Assuming $J = 19$ spot beams per satellite, I_0 is defined by

$$I_0 = 6I_{01} + 12I_{02}. \tag{60}$$

Typical values of I_{0_1} and I_{02} are 0.15 and 0.01, respectively, so that $I_0 = 2.02$. I_{01} represents the ratio of the multiple-access interference from an adjacent cell to the multiple-access interference from the cell-of-interest. Similarly, I_{0_2} is defined as the ratio of multiple-access interference from a cell in the second tier to the multiple-access interference from the cell-of-interest.

Assuming $c = 10$ dB and $P = 12$ dB (which corresponds to the required fading margin with perfect interleaving for a shadowed user to have comparable performance to that of nonshadowed user, [2]), for a per system PFD limit, we present in Table I some characteristic values of system parameters when orthogonal sequences are employed. Note that, because K_1 depends on B, for a given L, the degree to which orthogonality can be exploited varies with B (i.e., the rows of Table I correspond to different degrees of orthogonality). For specific values of shadowing conditions (represented by the value of B), the fourth and fifth columns correspond to the limiting performance of a single system (when $E_1/N_0 \to \infty$). The last two columns indicate the limiting values of capacity for a single system such that single system capacities less than these values result in n systems outperforming the single system. That is, when the orthogonality is maintained only on a per spot beam basis, corresponding to $I_1 = I_0 - 1$ for $K_1 \leq L$, any $n > 1$ achieves larger capacity than a single system when the capacity of that single system is smaller than the appropriate value given in the last two columns of Table I.

The capacity due to multiple service providers is shown in Figs. 14 and 15. In both figures, again corresponding to orthogonality only within each spot beam, capacities are normalized with respect to the processing gain L (maximum number of orthogonal sequences). In Fig. 14, n is taken to be 3, and a family of curves for different values of B shows the resulting capacity. Curves are plotted only up to the point where $n = 3$ yields larger capacity than $n = 1$. In Fig. 15, for the value of B equal to 0.2, the capacity is shown versus K_1/L for various values of n. These results for the downlink with orthogonal spreading indicate that a capacity improvement due to sharing is possible only when the capacity of the single system is relatively small to begin with, unlike the case when nonorthogonal spreading is employed whereby n systems always outperform a single system. That is, there is a penalty for spectrum sharing when orthogonality is employed, in that it results in a larger *relative* increase in the total multiple-access interference as seen by a mobile, compared to the case with nonorthogonal spreading. This can be seen by comparing (23) and (48). Because the second term in the denominator of (48) is less than the corresponding term in (23), the third term in the denominator of (48) has a proportionally larger effect than does the third term of (23). This, in turn, requires a larger transmit power per user for the same transmission quality, which results in a corresponding increase in the PFD and, thus, a reduction in the capacity.

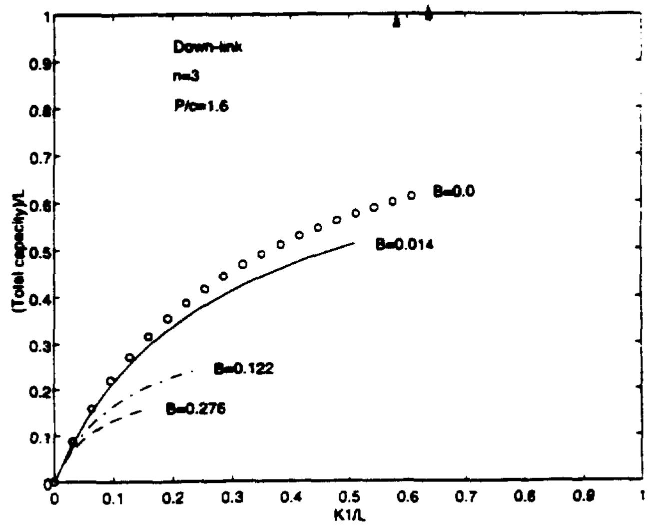

Fig. 14. Downlink total capacity when orthogonal spreading is employed; PFD constraint on a per system basis.

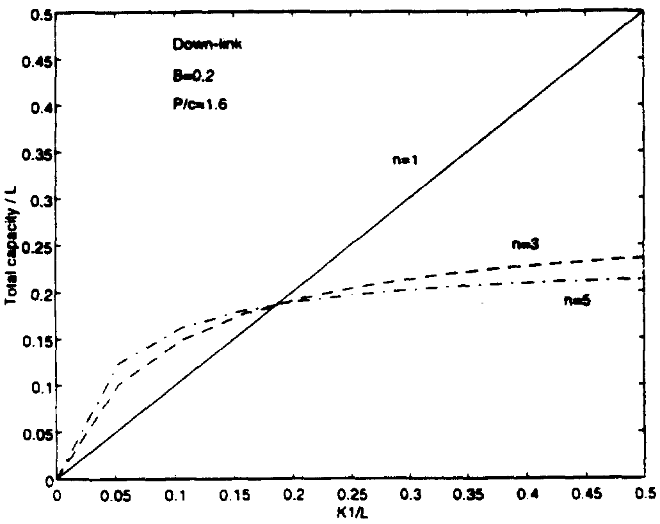

Fig. 15. Downlink total capacity when orthogonal spreading is employed; PFD constraint on a per system basis.

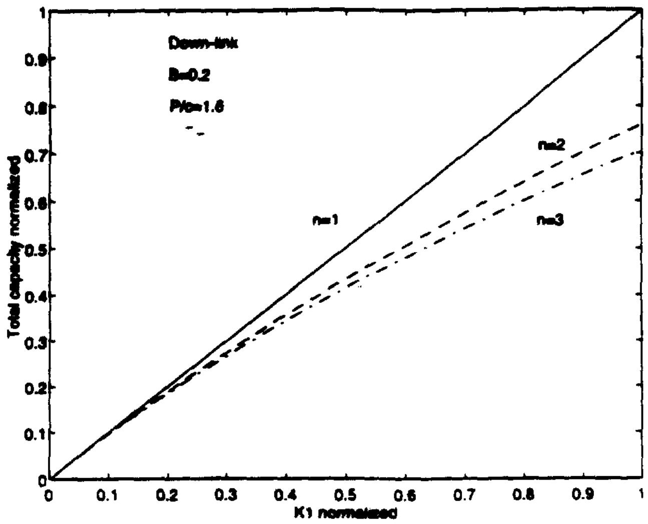

Fig. 16. Downlink total capacity with orthogonal spreading and aggregate PFD constraint; $B = 0.2$.

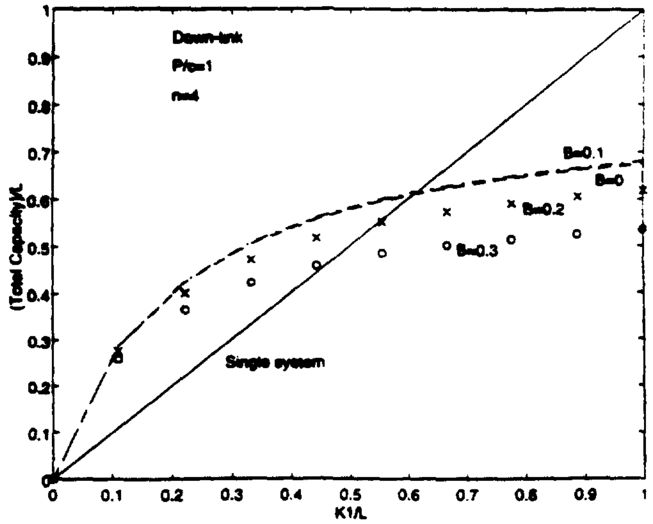

Fig. 18. Downlink total capacity with orthogonal spreading and double coverage; PFD constraint on a per system basis.

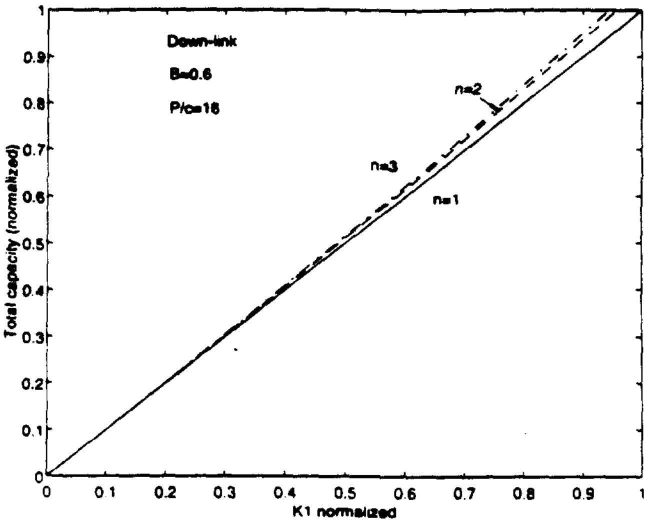

Fig. 17. Downlink total capacity with orthogonal spreading and aggregate PFD constraint; $B = 0.6$.

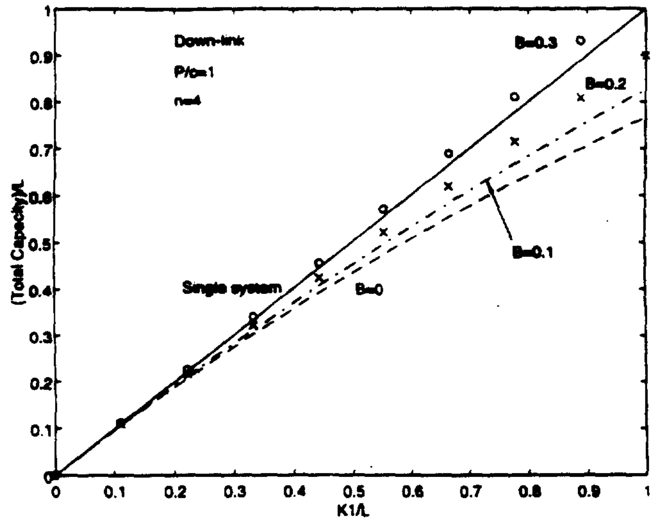

Fig. 19. Downlink total capacity with orthogonal spreading and double coverage; aggregate PFD constraint.

When the orthogonality is employed both by a single system and by multiple systems beyond just on a per spot beam basis (i.e., if $L > K_1$, then the orthogonality extends to more than one spot beam per set of orthogonal signals), and when $\frac{K_1}{K_{1,\infty}} < \frac{I_{1,\infty}}{I_0 A_3}$, (43) indicates that n systems ($n > 1$) always yields larger capacity than does a single system. However, for virtually any realistic set of parameter values, (44) indicates that $n = 1$ is optimum whenever $\frac{K_1}{K_{1,\infty}} > \frac{I_{1,\infty}}{I_0 A_3}$.

Now we consider the case in which orthogonal sequences are employed on the downlink and an aggregate PFD limit is imposed. When orthogonality is maintained only within each spot beam, then, if $A_3 < (1 - 1/I_0)$, n systems yield larger capacity than does a single system (see (47)). If the inequality is reversed, $n = 1$ is optimal. Figs. 16 and 17 compare the capacity of n systems with the capacity of a single system for $B = 0.2$ and $B = 0.6$, corresponding to capacity degradation and capacity improvement, respectively.

It is of interest at this point to give an intuitive explanation of results in Figs. 16 and 17, corresponding to an aggregate PFD limit. By increasing the percent shadowing in the system, the PFD increases due to an increase in the transmit power for shadowed users. With multiple systems, an increase in B results also in increased shadowing of multiple-access interference from other systems, as seen by a mobile. At some point the latter effect starts to dominate the former, and any further increase in B results in a smaller required average transmit power per user, for the same transmission quality. This, in turn, reduces the corresponding PFD, or, equivalently, results in an increase of capacity. It should be noted, however, that although a relative capacity improvement can be achieved with multiple systems sharing the same spectrum for relatively large values of B, the absolute capacity is decreasing with B, and it is of primary importance to reduce the fraction of shadowed users in the system. This can be accomplished by employing satellite diversity.

The effect of such a diversity configuration is twofold. First, by having two satellites separated in orbit, the probability of a mobile being shadowed to both satellites simultaneously is reduced from what it is to only one satellite. Further, when a specific mobile is shadowed to both satellites, the diversity gain enables the use of a smaller transmit power for the same performance, relative to the case when only a single path is available. Figs. 18 and 19 illustrate the results for the dual satellite diversity derived in the previous section; Fig. 18 corresponds to a PFD limit per satellite, and Fig. 19 corresponds to an aggregate limit. In both figures, $n = 4$, $P' = 1$, $P'' = c$, and both the abscissa and ordinate axes are normalized by the processing gain, L.

For convenience, a diagonal line labeled "single system" is shown. Using this as a perspective, any point above and to the left of that line corresponds to $nK_n > K_1$, while any point below and to the right corresponds $nK_n < K_1$. From Fig. 18, it is seen that for any of the shadow probabilities $B = 0, 0.1, 0.2$ or 0.3, there is a crossover point such that for K_1/L less than some value, multiple systems yield higher capacity, while for K_1/L greater than that value, a single system is superior. Alternately, from Fig. 19, a single system is preferable for all values of K_1/L for $B = 0, 0.1$ and 0.2, while multiple systems are better for $B = 0.3$.

If we compare Fig. 18 to Fig. 7, both of which correspond to the down-link with a PFD limit on a per satellite basis and such that orthogonal sequences on each spot beam are used, we see there is no qualitative difference between the two. That is, for a given value of B, a capacity threshold, say K_t, is reached, such that for $K_1 < K_t$, n systems achieve greater capacity, while for $K_1 > K_t$, a single system can support more users. The value of K_1 is, of course, a function of both B and whether or not diversity is employed, but qualitatively, the results are the same.

When we use an aggregate PFD limit, the relevant figures are Fig. 19 and Figs. 10 and 11. Once again, we see no qualitative difference in performance. With the aggregate PFD constraint, we now see a threshold, say B_t, of the probability of shadowing, such that $n > 1$ is better for $B > B_t$, and $n = 1$ is superior for $B < B_t$.

VII. Conclusion

Whether a single system or multiple systems achieves greater capacity is a function of a variety of parameters, among which are the degree of shadowing, the type of PFD limit, and the specific link under consideration (i.e., the uplink or the downlink). To succinctly summarize some of our key results, we list the following conclusions:

1) For an AWGN channel, when the PFD limit is on a per system basis, multiple systems always outperform a single system, on either the uplink or the downlink.
2) For an AWGN channel with an aggregate PFD limit, there is no difference in total capacity between multiple systems and a single system, on either the uplink or the downlink.
3) When there is shadowing present on the uplink, a single system always yields the highest capacity when an aggregate PFD is used; for a per system PFD, whether a single system or multiple systems result in greater capacity is a function of, among other things, the degree of shadowing.
4) When shadowing is present on the downlink, and when orthogonal sequences are used on a per spot beam basis, for either a per system or an aggregate PFD constraint, whether multiple systems achieve a higher net capacity than that of a single system is, again, a function of the degree of shadowing (among other things).

As indicated in the Introduction, if the intention of introducing a PFD limit is to control the amount of interference to terrestrial systems for the downlink, or to space systems for the uplink, it appears that an aggregate PFD limit is more appropriate. Under this condition, a single system provider is *always* more spectrally efficient on the uplink, and is more efficient for system parameters of most practical interest for the downlink. Indeed, even when the PFD limit is imposed on a per system basis, it appears that for well-designed systems (those that achieve relatively high capacity), a single system outperforms n systems in terms of capacity.

Appendix
PFD Limit Versus Normalized Capacity

In this Appendix, we establish a relationship between the normalized system capacity, which was used throughout the paper as a reference parameter, and several system parameters which are usually used to characterize communication systems. The relationship between the PFD limit and $K_1/K_{1,\infty}$ for the downlink can be found as follows (a similar derivation can be used the the uplink). From (21) and (25), we have

$$\frac{K_1}{K_{1,\infty}} = \left(1 + \frac{N_0 L}{K_1 E_1 I_0 A_2}\right)^{-1} \tag{A.1}$$

where

$$E_1 = P_1 T = \frac{P_1}{R} \tag{A.2}$$

P_1 corresponds to the received power of a single user, and R is the user's data rate in bps. The PFD is defined as power per meter per specified bandwidth. Specifically, the PFD limit specified by RR2566 is –142 dBW/m^2/4 kHz [4]. The total power received from K_1 users is $K_1 P_1$. Since the received power is equal to the product of the PFD and the antenna aperture, A_R, the maximum received power from K_1 users is related to the PFD limit by

$$K_1 P_1 = \frac{(\mathrm{PFD}) A_R W_{ss}}{4 \times 10^3} \tag{A.3}$$

where W_{ss} represents the spread bandwidth. One can then show, from (A.1)–(A.3), that

$$\frac{K_1}{K_{1,\infty}} = \left(1 + \frac{R N_0 L (4 \times 10^3)}{I_0 A_2 A_R (\mathrm{PFD}) W_{ss}}\right)^{-1} \tag{A.4}$$

or, equivalently,

$$\mathrm{PFD} = \frac{R N_0 L (4 \times 10^3)}{I_0 A_2 A_R (\mathrm{PFD}) \left(\frac{K_{1,\infty}}{K_1} - 1\right)}. \tag{A.5}$$

TABLE II
TYPICAL VALUES OF CAPACITY AS A FUNCTION OF PERCENTAGE SHADOWING

B	0.00	0.014	0.122	0.276
A_2	1	1.21	[illegible]	5.14
$K_1/K_{1,\infty}$	0.5	0.55	0.74	0.84
K_1/L	0.41	0.38	0.25	0.17

Example: Consider the following down-link parameters:
$R = 9600$ bps
$L = 130$ (numeric)
$A_R = -29$ dB(m^2)
$I_0 = 2.02$
$N_0 = -204$ dB(W/Hz)
PFD $= 142$ dB(W/m^2/Hz)
$W_{ss} = 1.25$ MHz (spread bandwidth).
From (A.5), one can obtain

$$\frac{K_1}{K_{1,\infty}} = \left(1 + \frac{0.488}{A_2}\right)^{-1}. \tag{A.6}$$

For different values of the shadowing factor B, the corresponding values of $K_1/K_{1,\infty}$ are shown in Table II.

As another example, consider the case when orthogonal sequences are used in the downlink, whereby the orthogonality is employed only on a per spot beam basis. Then, using a similar derivation as for (A.4), one can obtain

$$\frac{K_1}{L} = \frac{2}{\text{SNR}}\left[(I_0 - 1)A_2 + \frac{N_0RL(4 \times 10^3)}{(\text{PFD})A_RW_{ss}}\right]^{-1} \tag{A.7}$$

and for SNR $= 1.62$ (see [2]), the values of K_1/L, corresponding to the assumed PFD limit are given in the last row of Table II.

By comparing the last row in Table II and last column in Table I, it can be seen that, for our assumed system parameters, the capacity improvement with $n > 1$ is possible only for $B = 0.0$ and $B = 0.014$. For $B = 0.122$ and $B = 0.276$, the capacity of a single system is larger. Actually, it follows from (9), (10), (49), and (A.7) that a capacity improvement with sharing is possible only if the following inequality is satisfied

$$B^2(P-1)\left(1 - \frac{1}{c}\right) - B\left[\frac{1}{I_0}(P-1) - \left(1 - \frac{1}{c}\right)\right] + \frac{1}{I_0}\left[\frac{N_0RL \cdot 4 \times 10^3}{(\text{PFD})A_RW_{ss}} - 1\right] > 0. \tag{A.8}$$

For the set of parameters in our example, one can obtain that capacity improvement with sharing is possible only if either $B < 0.094$ or $B > 0.38$.

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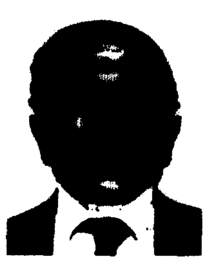
Branimir R. Vojcic (M'87) received the Diploma in electrical engineering, and the M.S. and D.Sc. degrees in 1980, 1986, and 1989, respectively, from the University of Belgrade, Yugoslavia. In 1986–1987, he was a graduate student at the George Washington University.

Since 1991 he has been at the George Washington University, where he is an Assistant Professor in the Department of Electrical Engineering and Computer Science. He teaches courses in digital communications, communication theory, and computer networks. His current research interests are the performance evaluation and modeling of terrestrial and satellite mobile communications, spread spectrum, multiuser detection, equalization, and wireless data networks.

Laurence B. Milstein (S'66–M'68–SM'77–F'85) for a photograph and biography, please see this JOURNAL, p. 212.



Raymond L. Pickholtz (S'54–A'55–M'60–SM'77–F'82) received the Ph.D. degree in electrical engineering from the Polytechnic Institute of Brooklyn in 1966.

He is Professor in and former Chairman of the Department of Electrical Engineering and Computer Science at the George Washington University. He was a researcher at RCA Laboratories and at ITT Laboratories. He was on the faculty of the Polytechnic Institute of Brooklyn and of Brooklyn College. He was a visiting professor at the Université du Quebec and the University of California.

Dr. Pickholtz is a Fellow of the American Association for the Advancement of Science (AAAS). He was an Editor for the IEEE TRANSACTIONS ON COMMUNICATIONS, and a Guest Editor for the special issues on *Computer Communications*, *Military Communications*, and *Spread-Spectrum Systems*. He is Editor of the *Telecommunication Series* (Computer Science, Rockville, MD). He has published scores of papers and has six U.S. patents. He is President of Telecommunications Associates, a research consulting firm specializing in communication system disciplines. He was elected a member of the Cosmos Club and Fellow of the Washington Academy of Sciences in 1986. In 1984, he received the IEEE Centennial Medal. In 1987, he was elected Vice-President, and in 1990 and 1991, as President of the IEEE Communications Society.

APPENDIX II

Report of Findings Regarding Studies Undertaken to Determine Displacement Impact Upon 2 GHz Terrestrial Stations

By

Carl T. Jones Corporation

CARL T. JONES
CORPORATION

REPORT OF FINDINGS REGARDING STUDIES UNDERTAKEN TO DETERMINE DISPLACEMENT IMPACT UPON 2 GHZ TERRESTRIAL STATIONS

I. Introduction

Carl T. Jones Corporation is an engineering services organization with extensive experience and capability in commercial broadcasting and other electronic communications media. The company, which became Carl T. Jones Corporation (CTJC) in January, 1984, originated in 1935 in Washington, D.C., and has continuously provided professional engineering consulting services from its time of origin to the present.

Principal interests and capabilities of the corporation are professional technical consulting services for the commercial broadcaster (AM, FM, and TV) and the U.S. Government, research and development in communications and electronics, research in requirements for communications and other support systems, communications system studies and design, and evaluation of communications equipment including Federal Communications Commission (FCC) and Canadian DOC equipment authorization testing.

Carl T. Jones Corporation has been authorized by Motorola Satellite Communications, Inc. ("Motorola") to undertake studies related to certain aspects of the proposed spectrum allotment changes set forth in E.T. Docket No. 95-18, *Amendment of Section 2.105 of the Commission's Rules to Allocate Spectrum at 2 GHz for Use by the*

Mobile-Satellite Service. The Notice of Proposed Rulemaking (NPRM) in the Docket was released on January 30, 1995.

II. Purpose

The action proposed in the Docket was initiated to allocate frequency spectrum for use be the mobile-satellite service at 2 GHz. This action would displace a number of existing 2 GHz users. Carl T. Jones Corporation has undertaken studies to determine the current user population in the affected frequency band 1990-2110 MHz and assess the cost associated with affected user migration and displacement to alternate frequency bands.

III. Background

The Commission proposes to reallocate 1990-2025 MHz (Earth-to-Space) to the mobile-satellite service (MSS). This frequency spectrum is currently occupied by Broadcast Auxiliary Service (BAS) licensees. The BAS licensees use these frequencies for Television Pickup, Television Studio-Transmitter-Link, Television Relay and Television Translator Relay stations.

Pursuant to Section 74.602 of the FCC Rules, there are three Frequency Bands allotted to microwave BAS facilities for use by television licensees. These frequency bands are designated as: Band A (1990 to 2110 MHz and 2450 to 2483.5 MHz); Band B (6875 to 7125 MHz) and Band D (12.7 to 13.25 GHz).